A Novel G-APD Based Camera for Imaging Air Cherenkov Telescopes: Concept, Realization and First Tests

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for the DWARF collaboration

guest talk

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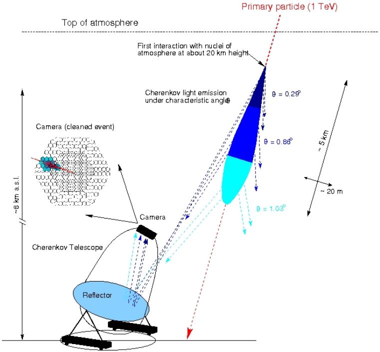
Introduction and Motivation

Imaging Air Cherenkov Telescopes (IACTs)



Imaging Technique

Shower Image Characteristics:

- Time distribution of Cherenkov photons: a few ns
- γ-ray energy is proportional to the number of produced Cherenkov photons.

Photo Detector Requirements:

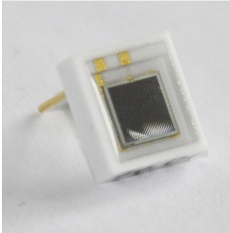
- Fast photo detectors
- high photon detection efficiency
- Robust (no ageing, background light, weather)
- High dynamic range (> 1000) desirable

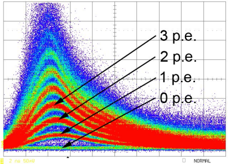
Geiger-mode Avalanche Photodiodes (G-APD)

Geiger-mode Avalanche Photodiodes (G-APD)

G-APD = Geiger-mode Avalanche Photodiode
also called SiPM, MPPC, PPD...

- Pixelized photon detector: each cell can detect single photons, the total signal is the sum of the identical single cell signals
- Statistical saturation
- Very stable, no aging found
- Several manufacturers: CPTA/Photonique, Hamamatsu, MPI Semiconductor Lab, Zecotec...



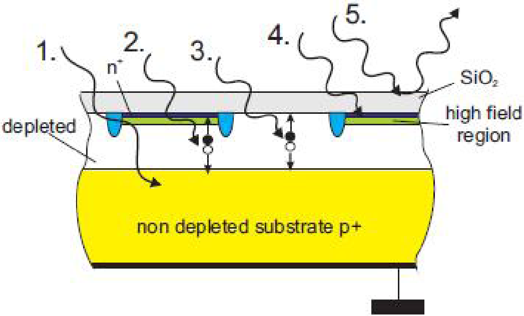


Hamamatsu MPPC S10362-33-50C

More information: see eg. D. Renker & E. Lorenz, JINST 4 P04004, (2009).

Working Principle

- incident photons generate free carriers in depletion zone
- trigger avalanche
- signal not proportional to number of incident photons (Geiger-mode)
- quenching resistor stops avalanche



Basic Properties

Advantages:

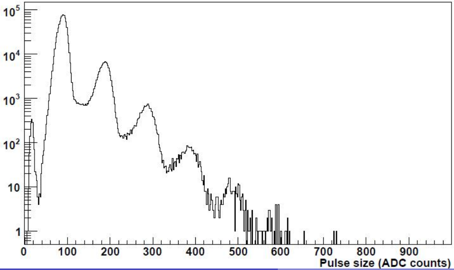
- Low bias voltage (< 100 V)
- High gain ($10^5 - 10^7$)
- Not damaged by bright light
- Light and robust
- High PDE (30-50%)
- No time-jitter (< 100 ps)
- Single photon resolution
- Independence of angle of incidence
- Insensitive to magnetic field

Disadvantages:

- Temperature dependent gain
  - $\approx 1\%$ / 0.1 K
- Optical crosstalk
  - $\approx 10\%$
- Dynamic range smaller than PMT
  - ≈ 1000
- No long term experience

Crosstalk, dark counts and afterpulses

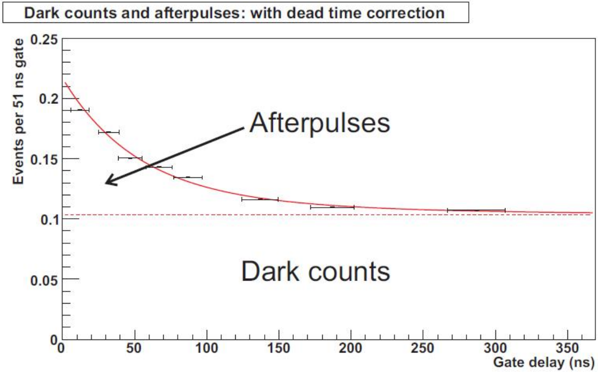
- Dark counts
  - cells triggered by any free carrier (e.g. thermally generated)
  - Rate: $\sim$100 kHz - MHz / mm^2 at room temperature.
- Afterpulses
  - delayed release of carriers trapped during a breakdown
  - Afterpulse probability 5 - 20% depending on the gain.
- Crosstalk
  - avalanche can emit IR photons $\Rightarrow$ trigger neighbouring cells.
  - Crosstalk probability 5 - 20% depending on the gain.



Measured spectrum of dark counts and afterpulses (crosstalk 13%).
Peaks of up to 6 triggered cells can be discerned.

time distribution

- Dark counts
  - random time distribution
- Afterpulses
  - exponentially decreasing probability

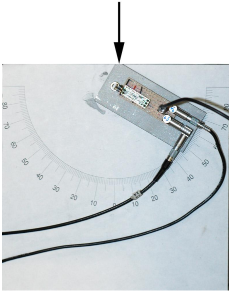


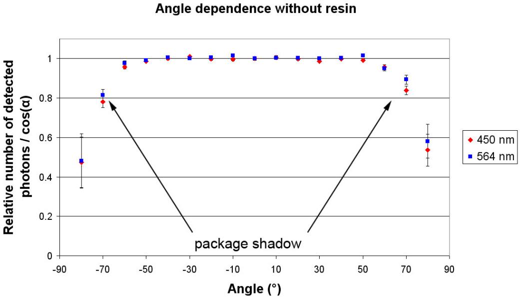
Number of pulses per gate for variable delays after an initial pulse.
The number of pulses decreases exponentially to the level of dark counts.

$\Rightarrow$ Afterpulses are not a problem.

Angular dependence of the PDE

- Light concentrators cover inactive area(Braun^{+} ICRC 2009).
- Solid cones allow higher concentration ratios than usual hollow cones
  $\Rightarrow$ larger angles of incidence at the photodetector surface.

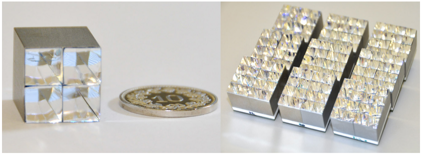




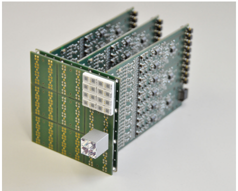
$\Rightarrow$ No angular dependence found within errors ($\sim$ 1%).

G-APD Camera Prototype Module

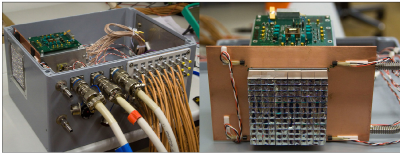
Setup of the Prototype Module



Each G-APD has 1 Winston Cone (light collector). 4 G-APDs together form one pixel, corresponding to one readout channel

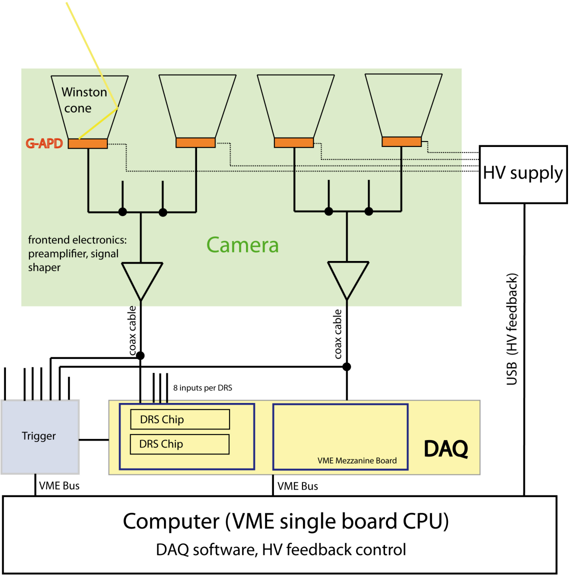


The G-APDs are connected to 3 preamplifier boards (preamplification, bias voltage distribution, summation of each 4 G-APD signals to one readout pixel)



Cooling plate and weather proof camera box

Readout and Trigger System of Prototype



Data Acquisition (DAQ):

- Domino Ring Sampler (DRS2)
- Analog pipeline: 1024 cells
- 2 GHz, possible rates at 0.5 – 2 GHz
- Multiplexed 12 bit ADC
- VME housing and CPU

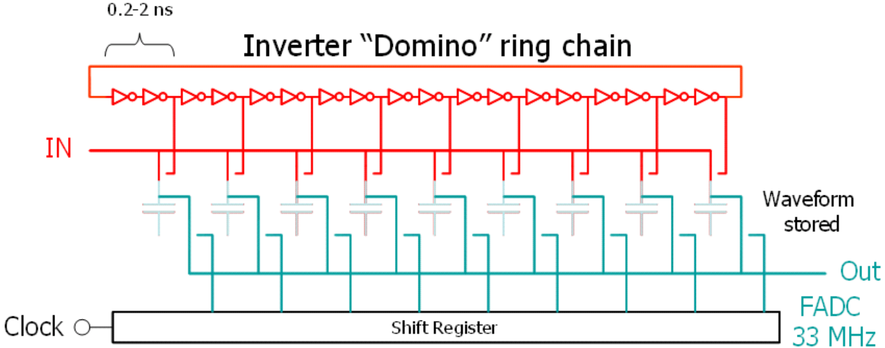
Trigger System:

- Majority coincidence of 16 innermost pixels e.g. 3 or 4 out of 16.
- VME CFD and scaler

DRS Working Principle

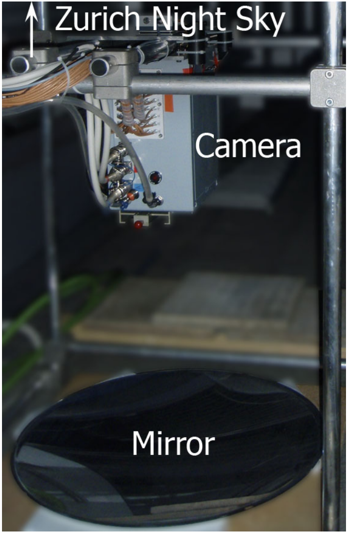
A switched capacitor array

- 9 channels
- 1024 cells



Measurements with Prototype

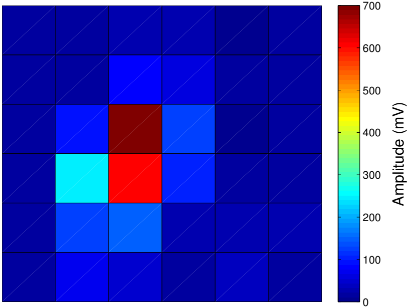
"Telescope" Setup at ETH Zurich



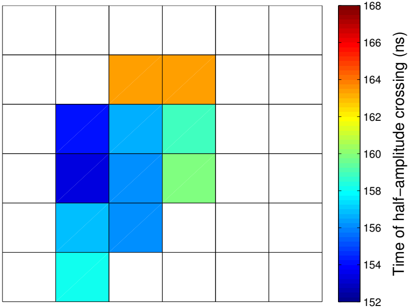
- optics:
  - pixel size 14.4 x 14.4 mm^2
  - 90 cm mirror
  - $f/D \approx 0.9$
  - plate-scale $\approx$ 1.57 cm/deg
- High night sky background: $\sim$ 1.2 GHz / pixel
- Temperatur stabilized (different runs with temperatures between 8-22°C).
- Changing weather conditions

Recorded Cosmic Air Showers - Run# 206, Event# 14

Max. Amplitude

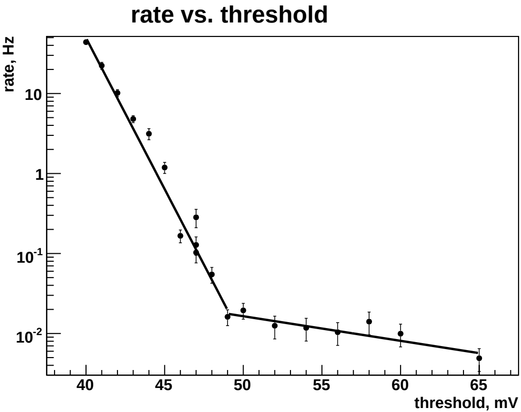


Timing



- Arrival time defined as time of half amplitude crossing
- Only pixels with amplitudes $> 60\,\mathrm{mV}$ considered for time calculation

Rate Scan (night of September 23)



- Thresholds for individual pixels varied
- Majority trigger: 3 out of 16

- Rate corrected for deadtime of readout system (here 25 ms)
- Correlation with external PMTs cross-checked ($\pm$ 7 m from camera)

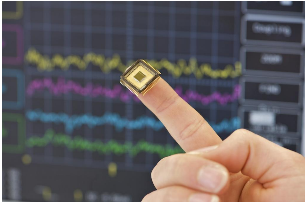
Summary

- A 36 pixel (144 G-APDs) prototype G-APD camera to measure Cherenkov light images from extended air showers has been constructed and commissioned
- Operation at room temperatures ($8^\circ - 22^\circ$C) and high night sky background (1.2 GHz/pixel) possible
- First air showers have been recorded (selftriggered)
- A rate scan (rate vs. trigger threshold) shows the expected behaviour: a steep NSB spectrum, going over in a flat spectrum originating from cosmic ray shower triggers

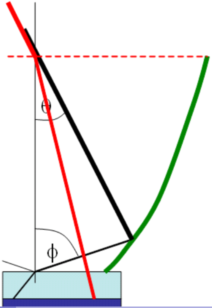
The DWARF Camera

Work in Progress: FACT

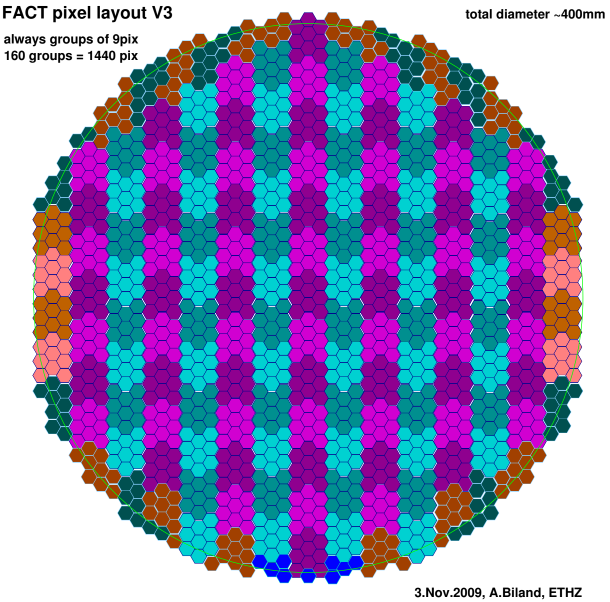
- We are devoloping a camera with a field of view of 4.3°
  FACT: First Avalanche Photodiode Camera Test
- Optimized for a 3.5 m telescope (e.g. HEGRA CT3, La Palma, Spain)
- Investigation of solid Winston cones
  ⇒ Larger opening angles possible
  ⇒ Single G-APD readout
- Modular design: Preamplifier boards - trigger boards - DAQ boards stackable.
- Data transfer from camera to counting house via ethernet
- Readout based on DRS4 chip



DRS4: drs.web.psi.ch

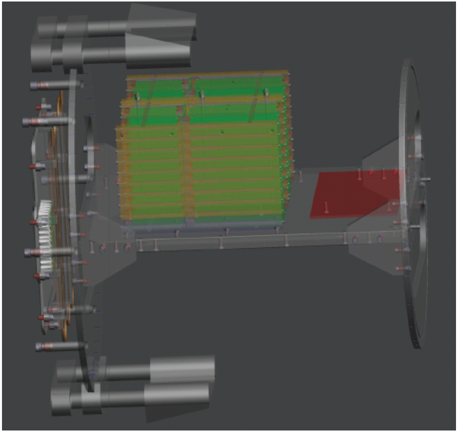


pixel arrangement



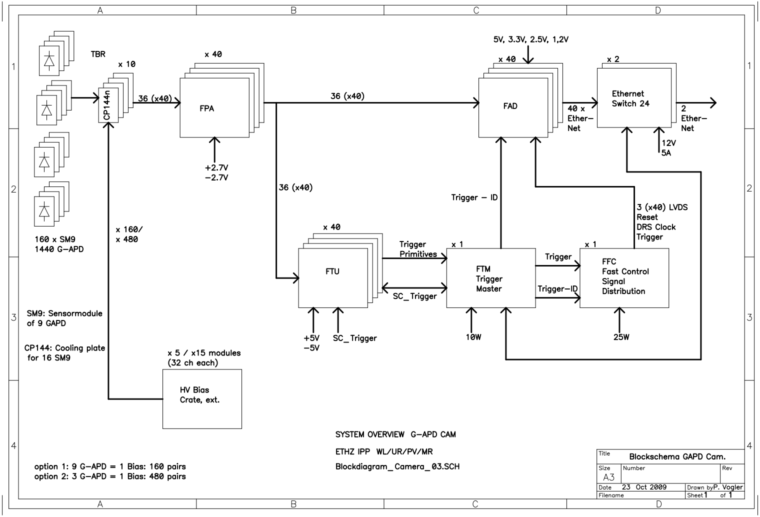
The 4.3° Camera

- 1440 pixels each with a FOV of 0.11°
- sampling rate 2 GHz (pipeline depth 500 ns)
- power consumption ∼1.5 kW
- diameter ∼500mm
- length ∼600mm
- weight ∼200kg
- focal plane diameter 360mm

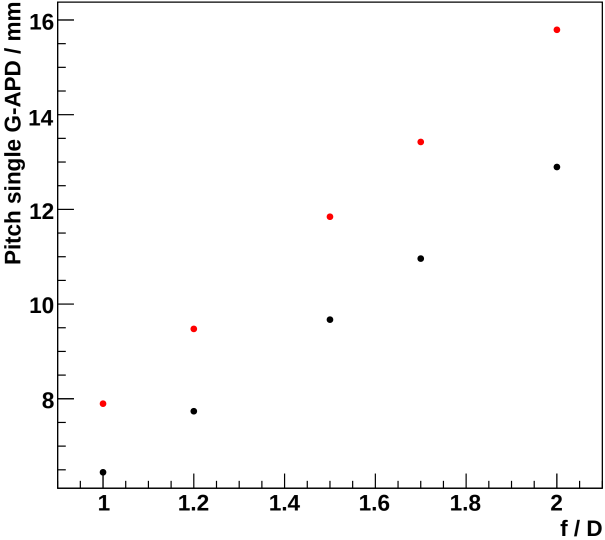


thank you for your attention
(& patience)

Backup: Readout Electronics (Block Diagram)



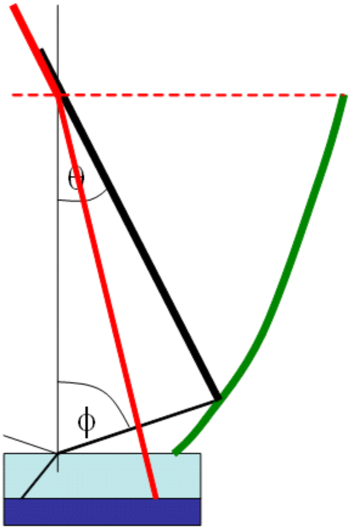
Backup: Winston Cones (Simulations)



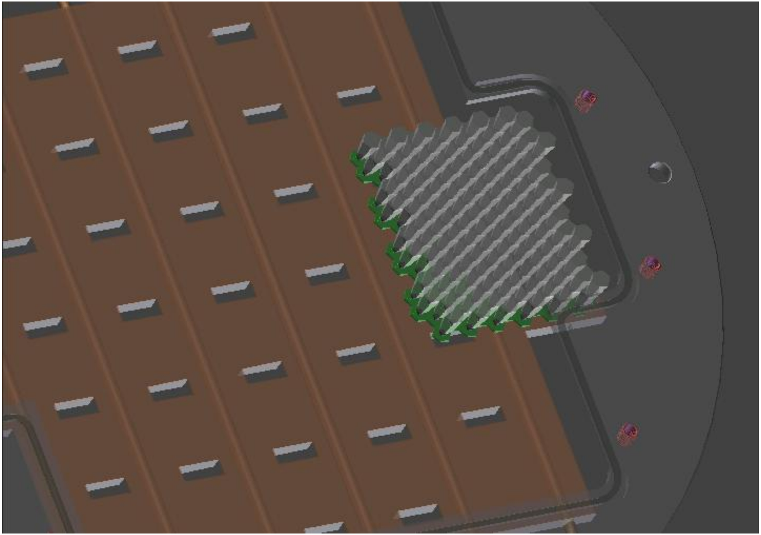
- Black:
  Open cones
- Red:
  Solid cones
- 9 mm^2 G-APDs assumed

Backup: solid vs. hollow

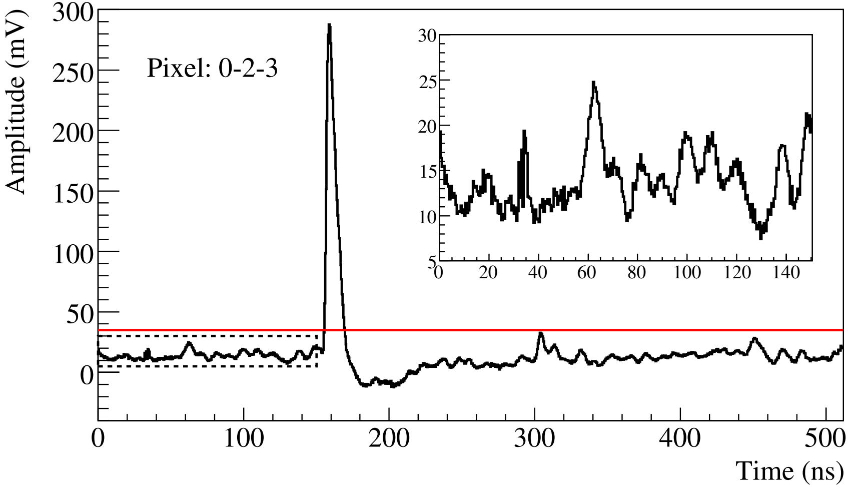
- Pros
  - primary refraction ⇒ larger input angles accepted
  - larger collection efficiency
  - less Fresnel reflection than at layer near detector
  - mass production
- typical caveats
  - false traces by muons ⇒ high line signal
  - UV transmittance ⇒ select material
  - more NSB ⇐ in case of "‘wrong shape"’



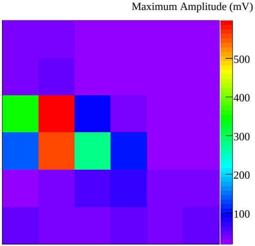
Backup: Photodetector plane



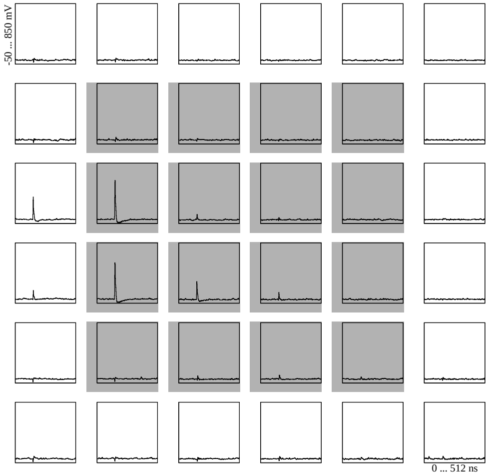
Backup: Cherenkov and NSB Signals



Backup: Recorded Cosmic Air Showers - Run# 206, Event# 8



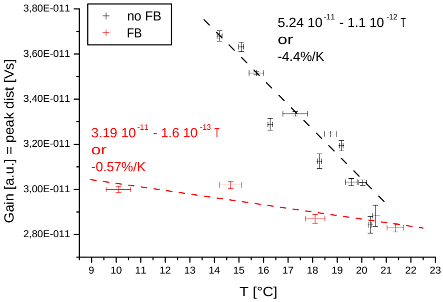
- 40 mV single pixel threshold ($\sim$ 7 p.e.)
- Majority 4 out of 16
- 1-3 kHz trigger rate per pixel
- $\sim$ 0.02 Hz total rate
- 2 GHz sampl. freq.

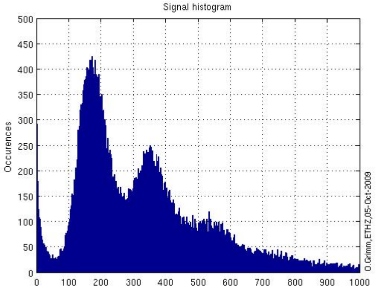


Horizontal: 0 ... 512 ns, Vertical: -50 ... 850 mV

Backup: Feedback Measurements and Dark Count Spectrum

- LED signals used for feedback system
- Gain from dark count spectrum ("singles")
- No digitization (DRS2 resolution not sufficient)





- Dark count spectrum with DRS2 digitization possible with ...
- ... additional 9x analog ampl.
- Baseline corr. (event-by-event)
- Better resolution with DRS4

Backup: solid vs. hollow

- Pros
    - primary refraction ⇒ larger input angles accepted
    - larger collection efficiency
    - less Fresnel reflection than at layer near detector
    - mass production
- typical caveats
    - false traces by muons ⇒ high line signal
    - UV transmittance ⇒ select material
    - more NSB ⇐ in case of "'wrong shape"'